STUDY ON CO_2 EMISSIONS OF PAVEMENT RECYCLING METHODS

Atsushi KAWAKAMI, Hiroyuki NITTA, Takashi KANOU and Kazuyuki KUBO
Pavement Research Team
Public Works Research Institute
1-6 Minamihara, Tsukuba-shi, Ibaraki, Japan
kawakami@pwri.go.jp

ABSTRACT

In Japan, reclaimed asphalt pavement (RAP) has been used, and the recycling rate of those is now 99%. It means that the asphalt pavement is an effective recycling material. However, the effectiveness of aggregate recycling in terms of CO_2 emissions remains unclear and the total environmental load including material production, transportation, paving work, and waste disposal is not known.
In this study, the CO_2 emissions of pavement recycle methods were estimated for three cases using virgin aggregates, plant recycling aggregates, or in-place recycling. The results showed that the CO_2 emissions when using recycled aggregates were less than when using virgin materials, and were far less in the case of in-place recycling, although the CO_2 emissions sometimes increase when the machines for the in-place recycling need to be transported long distances. Thus, recycling methods should be selected in consideration of environmental loads.

1. Introduction

As global warming and other environmental issues have gained greater attention, various efforts have been made to develop technologies for reducing environmental load in diverse fields. Recycling is one such means, and in the field of pavement in Japan, aggregate has been recycled for a long time. At present, asphalt pavement aggregates removed from paved roadways are recycled 99%.[1)]

Pavement recycling methods in Japan include plant recycling and in-place recycling, with the majority currently done by plant recycling. These recycling methods have attained a high recycling rate. Nevertheless, regarding global warming and CO_2 emissions in particular, their effectiveness has not yet been fully identified. Although the CO_2 emissions involved in pavement recycling have been examined,[2)] the details of recycling methods and estimation conditions were not clearly, and the environmental loads throughout the lifecycle including materials production, transportation, construction, and waste disposal have not yet been identified.

This paper reports on the results of estimating the amount of CO_2 emissions generated by pavement repair works using either conventional plant recycling or in-place recycling which reportedly generates less environmental loads, together with the results of analyzing the causes of increased environmental loads.

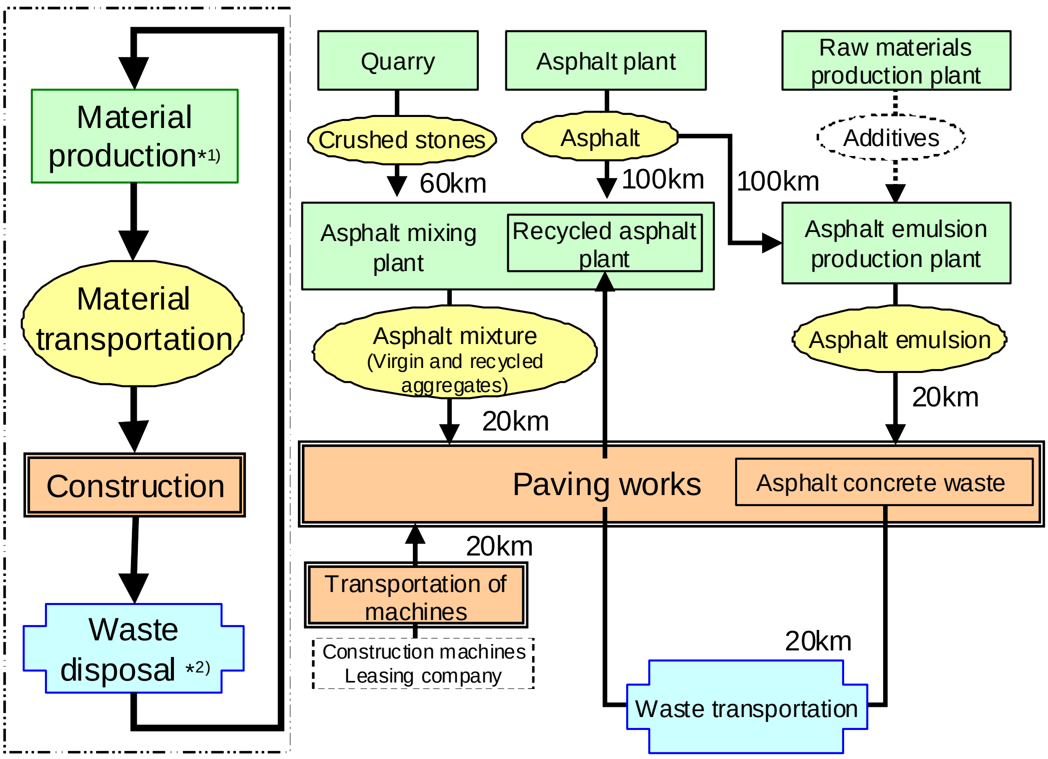
2. Outline and conditions of estimation

The pavement repair work methods used for estimating the CO_2 emissions in this study were cut-and-overlay, which is a general method using plant recycling with recycled aggregates. The other method is in-place surface course recycling, which is an in-place recycling method. Some variations were made to the case studies for comparing various effects, e.g., the use of virgin aggregates and recycled aggregates, change of the mix ratio of recycled aggregates, and transportation of machines specially designed for the in-place surface course recycling in various places nationwide.

The cycle from materials production to waste disposal for pavement repair works was examined, the quantities of materials, machines, and fuel used or consumed were estimated. The estimated figures were multiplied by the basic units of environmental loads to obtain the amount of CO_2 emissions. The basic units of all environmental loads emitted throughout the life from materials procurement to production obtained by the summation method, were selected from existing literature for this study. When unavailable in the existing literature, the basic units of environmental loads were determined by interviewing manufacturers.

(1) Range of estimation

The stages of pavement works examined in this study were set up as shown in **Figure 1**, being classified by the stages of CO_2 emissions, i.e., material production, material transportation, construction, and waste disposal.



Notes:

*1) Material production includes the process from acquisition to processing of raw materials.

*2) Waste disposal means the transportation of asphalt concrete waste (transportation of waste materials to the plant for producing recycled aggregates).

Figure 1. Range for examining the environmental loads of pavement works

In consideration of the present circumstances in Japan, the distance of transporting materials was set as 100 km for asphalt, 60 km for crushed stones (virgin aggregates), and 20 km for asphalt mixture. These are

average distances, and may vary by region.

Regarding waste disposal, all asphalt concrete waste were considered to be transported to a plant that produces recycled aggregates, since almost all aggregates of existing asphalt pavements are being recycled today.

As shown in **Table 1,** estimations were conducted using cut-and-overlay and in-place surface course recycling by following three cases. Case 1: cut-and-overlay using virgin aggregates; Case 2: cut-and-overlay using recycled aggregates produced at a recycled asphalt plant; and Case 3: in-place surface course recycling (remix method).

The mix ratio of recycled aggregates in RAP was set to 60% in Case 2 based on the average in urban areas in Japan.

Table 1. Cases used for estimation

<table>
<tr><td rowspan="2">Cases</td><td colspan="3">Examination of methods for repairing the surface course</td></tr>
<tr><td>Case 1</td><td>Case 2</td><td>Case 3</td></tr>
<tr><td rowspan="2">Repair method</td><td>Virgin aggregates (control)</td><td>Plant recycling method</td><td rowspan="2">In-place surface course recycling method (Remix)</td></tr>
<tr><td colspan="2">(Cut-and-overlay)</td></tr>
<tr><td>Replacing thickness</td><td colspan="3">Cutting off the existing pavement by 3 cm in thickness and overlaying new pavement with 5 cm in thickness</td></tr>
<tr><td>Mix ratio of recycled aggregates</td><td>0%</td><td>60%</td><td>(60%)</td></tr>
</table>

(2) Scale of paving works

The paving works were conducted on a 3.25 m-wide, 200 m-long, 2-lane roadway (work area of 1,300 m2). The existing asphalt pavement of 3 cm in thickness was cut out, and new pavement of 5 cm in thickness was overlaid.

(3) Quantity of materials and machines used

The quantity of materials and number of machines used for paving works, as well as the amount of fuel consumption, were calculated based on the scale of paving works, the amount of materials transported, and the Manual of Standard Quantity Surveying for Civil Engineering Works compiled by the Ministry of Land, Infrastructure, Transport and Tourism of Japan (MLIT)[3)] and other references. This manual was created to enable government and other public offices to conduct quantity surveys to estimate construction costs, as well as the conditions of materials to be used for public works, appropriate machines for respective pavement methods, and the quantities required (**Table 2** and **Table 3**).

The fuel consumption of road heaters used for in-place surface course recycling was set based on interviews with paving companies, because such interviews showed that it greatly varied depending on the machine.

Table 2. Specifications of materials used

Name	Specifications
Asphalt mixture	2.35 t/m^3 standard density, 0.07% loss rate, 5.5% asphalt quantity (the same rate applies to the old Asphalt mixture), and 2.7 t/m^3 unit weight of crushed stones
Asphalt emulsion	1.26 L/m^2 of prime coat spraying, and 14% in-place surface course rejuvenator (for the old asphalt)

Table 3. Machines used and their fuel consumption

Equipment and machine	Fuel type	Fuel consumption rate*1)
Road cutter	Diesel	0.132 L/m^2
Road sweeping vehicle	Diesel	0.039 L/m^2
Asphalt finisher	Diesel	0.019 – 0.053 L/m^2
Road roller	Diesel	0.015 – 0.030 L/m^2
Tire roller	Diesel	0.018 – 0.036 L/m^2
Vibratory roller	Diesel	0.031 L/m^2
Road heater (for heating)*2)	Kerosene	0.8 – 0.16 L/m^2
	LPG	1.000 kg/m^2
In-place surface course recycling equipment	Diesel	0.065 L/m^2
Dump truck (2 t – 25 t)	Diesel	4.90 – 19.72 L/h

Notes:

*1) Fuel consumption rates were calculated based on the amount of work execution per day and the amount of fuel consumption per operating day.

*2) The amount of fuel consumption of the road heater (for heating mixture) was set up based on data obtained by interviews with manufacturers.

(4) Basic units of environmental loads

The basic units of environmental loads of materials used for paving works were determined using figures already published or registered in existing databases, which had been obtained by the summation method as shown in **Table 4**.

As there were no figures for asphalt emulsion in the literature, producers were interviewed. Consequently, the Asphalt emulsion was made by asphalt, water, hydrochloric acid, and surfactant. The composition ratio was 50:48:1:1. The power consumed by the emulsificator for mixing constituents was set to 0.03 kWh/kg. The transportation of hydrochloric acid and surfactant was not taken into consideration because the fuel consumption was negligible.

As for other materials not shown in **Table 4**, rejuvenators for RAP could be used as an option. In the reference,[6] from which the basic units of environmental loads of asphalt were determined, the basic units of environmental loads of all refined petroleum products are the same. Accordingly, the basic units of environmental loads of rejuvenators were considered to be roughly the same, and so the amount of rejuvenators used was included in the amount of asphalt.

Table 4. Basic units of environmental loads

Item	(Unit)	CO_2 emissions ($kg\text{-}CO_2$)	Source
Electric power	kWh	4.00E - 01	JEMAI-LCA*1
Gasoline	L	2.47E + 00	
Diesel	L	2.69E + 00	
Asphalt	kg	2.48E - 01	Reference 4
Crushed stone (virgin aggregates)	t	9.05E - 01	
Recycled aggregate	t	4.28E + 00	
Asphalt mixture	t	2.62E + 01	
Recycled Asphalt mixture	t	2.89E + 01	
Asphalt emulsion	kg	1.60E - 01	Summation method
Industrial water	m^3	1.00E - 01	JEMAI-LCA
Hydrochloric acid	kg	1.08E + 00	JEMAI-LCA
Surfactant	kg	1.03E + 00	Reference 5*2

Note:

*1) LCA software developed by the Research Center for Life Cycle Assessment, National Institute of Advanced Industrial Science and Technology (AIST) and Japan Environmental Management Association for Industry (JEMAI).

*2) The basic unit of coconut oil fatty acid was used as a substitute for that of surfactant, because appropriate figures for constituents and production processes of surfactant were not available.

3. Results of estimating the CO_2 emissions

Table 5 shows the results of estimating the material consumption in the respective cases based on the scale of pavement works established in Section 2. (2), as well as the quantities of materials and machines used and their fuel consumption established in Section 2. (3). The CO_2 emissions were estimated (**Table 6** and **Figure 2**) by multiplying the amount of material consumption by the basic units of environmental loads (**Table 4**).

The results of classifying the environmental loads into the respective CO_2 emission stages in pavement works, i.e., "material production," "material transportation," "construction," and "waste disposal," showed that the CO_2 emissions in the stage of material production was the greatest in all three cases, and in particular the CO_2 emissions in Cases 1 and 2 accounted for approximately 70% of the total. Regarding the stage of material transportation, the CO_2 emissions in Case 2 accounted for 60% of those in Case 1. The CO_2 emissions decreased because the use of recycled aggregates in place of virgin materials reduced the transportation distances. The departure point of transportation was changed from the quarries to the paving work site. In Case 3, the CO_2 emissions during paving work execution were greater even though waste transportation was not required and less material transportation was needed than in Cases 1 and 2.

Table 5. Amounts of material consumption in the respective cases

Emission stage	Quantity of materials					
				Case 1	Case 2	Case 3
Material production	Asphalt mixture			163.4 t	163.4 t	61.1 t
		Asphalt		8.9 t	3.6 t	3.4 t
		Crushed stone (virgin material)		154.5 t	61.8 t	57.7 t
		Recycled aggregate		-	98.0 t	-
	Asphalt emulsion			1,638.0 L	1,638.0 L	705.7 L
Material transportation	Diesel			1,187.2 L	646.0 L	482.0 L
Construction	Machine transportation		Diesel	99 L	99 L	100.0 L
	Paving work		Diesel	300.9 L	300.9 L	295.2 L
			Kerosene*	-	-	1,560.0 L
			LPG*			1.3 t
Waste disposal	Waste transportation		Diesel	131.2 L	131.2 L	-

Note:

* Kerosene and LPG fuels are used for the road heater (for heating), for which average figures are used for environmental loads.

Table 6. Calculated results of environmental loads for the respective paving methods

Stage of emissions		Case 1	Case 2	Case 3
Material production		6.67E + 03	6.08E + 03	2.62E + 03
Material transportation		3.19E + 03	1.73E + 03	1.29E + 03
Construction	Machine transportation	2.66E + 02	2.66E + 02	2.68E + 02
	Paving work	8.08E + 02	8.08E + 02	4.59E + 03
Waste disposal	Waste transportation	3.52E + 02	3.52E + 02	0.00E + 00
Total		1.13E + 04	9.24E + 03	8.77E + 03

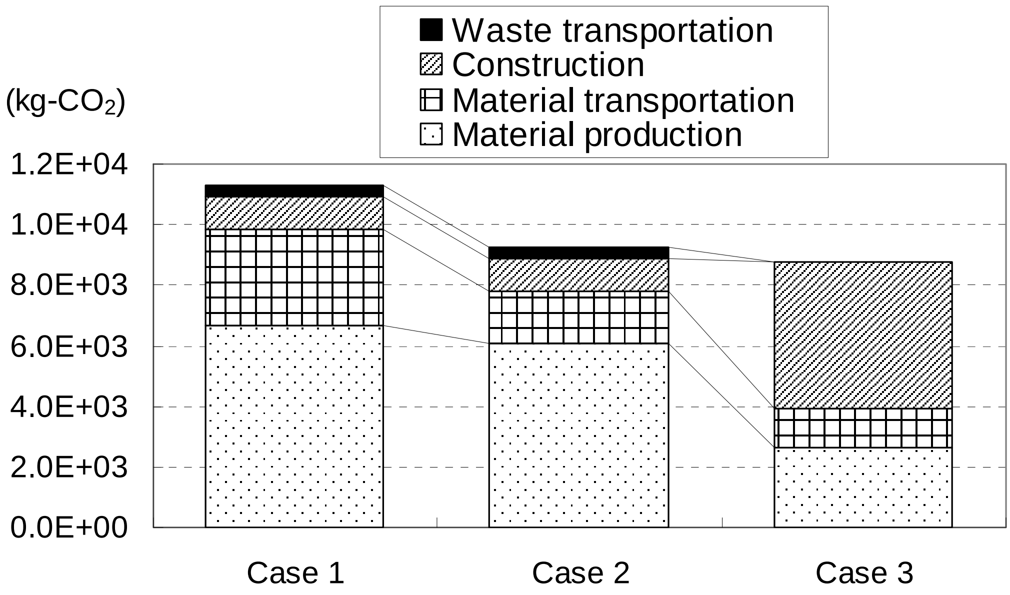


Figure 2. CO_2 emissions in the case1 to 3

(1) Comparison between virgin aggregates and recycled aggregates with cut-and-overlay

Concerning the cut-and-overlay, the amount of CO_2 emissions was compared between Case 1 which used virgin aggregates and Case 2 which used recycled aggregates.

As the work process in Cases 1 and 2 from the stage of construction (paving work, and machine transportation) to the stage of waste disposal is identical, the amount of the CO_2 emissions is the same in these two cases. Accordingly, the CO_2 emissions from the stage of material production to the stage of material transportation were compared (**Figure 3**). The material production stage comprises the production of asphalt, aggregates, asphalt mixtures, asphalt emulsion. The results showed that the production of asphalt and asphalt mixture accounted for most of the CO_2 emissions in this stage.

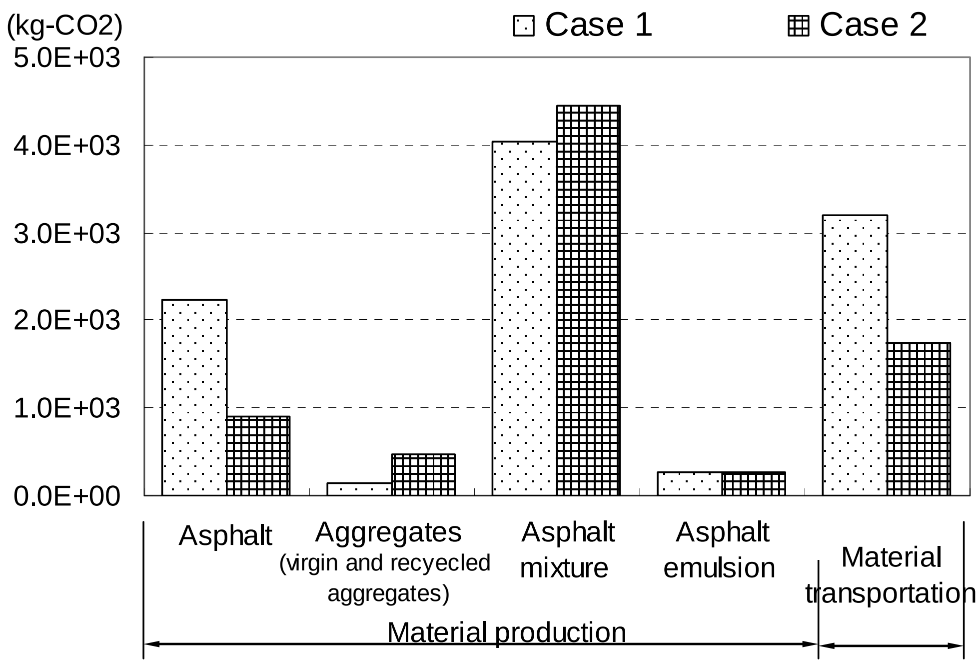


Figure 3. Comparison of CO_2 emissions between Cases 1 and 2
(for the material production and material transportation stages)

The basic units of environmental loads show in **Table 4.** It shows that the production of recycled aggregates is greater than virgin aggregates. Furthermore, the production of recycled asphalt mixture is also greater than asphalt mixture using virgin aggregates. Thus, in the initial stage of our study, there was concern that the CO_2 emissions when using recycled aggregates might be greater than when using virgin materials. In fact, the CO_2 emissions during aggregate production and asphalt mixture production in Case 2 were greater than in Case 1. Nonetheless, the total CO_2 emissions during material production were actually decreased because the decrease in the CO_2 emissions of asphalt surpassed the increase in the CO_2 emissions mentioned above. Furthermore, the total CO_2 emission in Case 2 was less than in Case 1 thanks to the reduction in material transportation.

(2) Effect of the difference in the mix ratio of recycled aggregates in plant recycling on the CO_2 emissions

The effect of the mix ratio of recycled aggregates on the CO_2 emissions in Case 2 was estimated. This mix ratio was initially set to 60%, which is the average in urban areas, and estimation was also conducted for the mix ratio of 40% which is the nationwide average including local areas, and for the mix ratio of 80% assuming that the recycling rate will probably increase in the future.

Figure 4 shows the results of the estimation. The overall CO_2 emissions are shown by bars, and the quantities are shown on the right axis. In addition, the CO_2 emissions of asphalt, aggregates (virgin and recycled aggregates), and asphalt mixture during material production, which change with the mix ratio of recycled aggregates, as well as those during material transportation, were extracted and plotted by broken lines.

These lines show that the CO_2 emissions during aggregate production gradually increased, but those of the asphalt production and material transportation decreased greatly. As for the aggregate production, the CO_2 emissions slightly increased when virgin aggregates were used instead of recycled aggregates. The decrease in CO_2 emissions of asphalt production was due to the amount of asphalt used was decreased because of the mix ratio of recycled aggregates was increased. On the other hand, the decrease in CO_2 emissions during material transportation was due to the decrease in the fuel consumption of trucks for transporting virgin aggregates and asphalt. Consequently, total CO_2 emissions decreased.

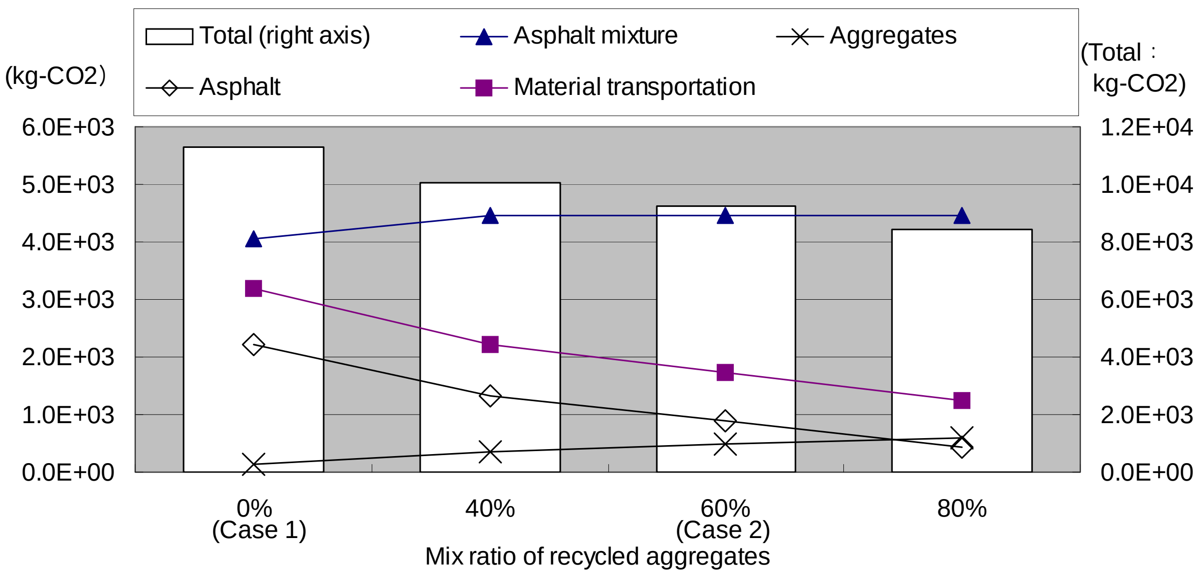


Figure 4. Comparison of CO_2 emissions by the mix ratio of recycled aggregates

(3) Comparison between cut-and-overlay and in-place surface course recycling

As shown in **Figure 2**, the amount of CO_2 emissions was estimated to be small for in-place surface course recycling in Case 3. However, the CO_2 emissions of construction were considerably high in comparison with cut-and-overlay in Cases 1 and 2. This is because, with the in-place surface course recycling, a series of paving processes, including heating and pulverizing the existing pavement and mixing it with virgin asphalt mixture, are done on site. Specifically, these two paving methods cannot be compared based only on the CO_2 emissions during work execution, because the production of recycled aggregates and asphalt mixture is included in the stage of material production in the case of cut-and-overlay, while it is included in the stage of paving works in the case of in-place surface course recycling.

Therefore, these two paving methods were compared by extracting the CO_2 emissions in the stages of material production and paving works (**Figure 5**). As a result, the difference in CO_2 emissions decreased, with those of in-place surface course recycling remaining greater. This is due to the huge fuel consumption for heating by the road heater on site in the case of in-place surface course recycling, suggesting that blanket production of recycled aggregates and recycled asphalt mixture improves efficiency. As mentioned before, however, the environmental loads of in-place surface course recycling are smaller, because this method requires the transportation of no waste but only a small amount of materials, thereby reducing the total CO_2 emissions.

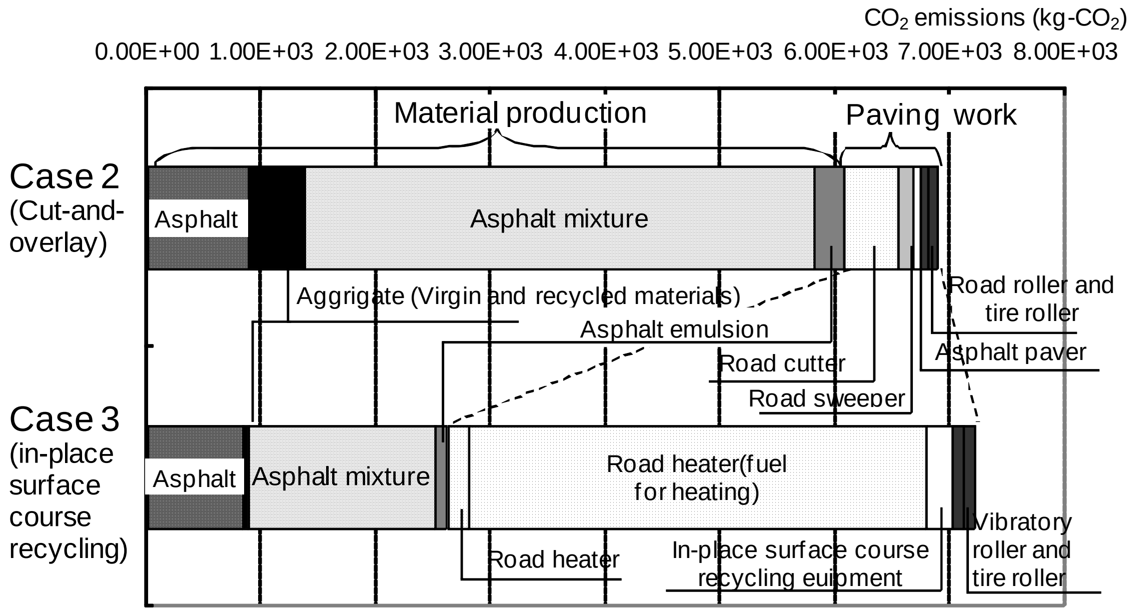


Figure 5. Comparison of CO_2 emissions between Cases 2 and 3 (for the material production and paving works stages)

However, there are not enough in-place surface course recycling machines nationwide, so the equipment must sometimes be transported long distances to other sites. Therefore, the effect of transportation distance on environmental load was examined. The calculations assumed that the in-place surface course recycling equipment was transported overland by a 25 t dump truck powered by diesel with a mileage of 19.720 L/h when driven at 25 km/h for distances of 500 km or 1,000 km. Specifically, only the diesel fuel consumption required for transportation was set to 25 times and 50 times the basic case (20 km) in proportion to the distance covered. In addition, as fuel-efficient road heaters (for heating) have recently been developed, a case with minimum fuel consumption was estimated. The results are shown in **Figure 6**.

The CO_2 emissions in Case 3, for which the average road heater fuel consumption was used, were equivalent to those in Case 1 when the distance covered was approximately 600 km, and were equivalent to

those in Case 2 when the distance covered was approximately 150 km. This showed that even in-place surface course recycling generates large environmental loads due to transportation of equipment and machines.

The line of CO_2 emissions of the case with minimum fuel consumption crossed the line of Case 1 at a distance of 900 km, and crossed that of Case 2 at approximately 500 km. Hence, fuel-efficient road heaters will lessen the CO_2 emissions, and the difference in fuel consumption efficiency of road heaters greatly affects the environmental loads.

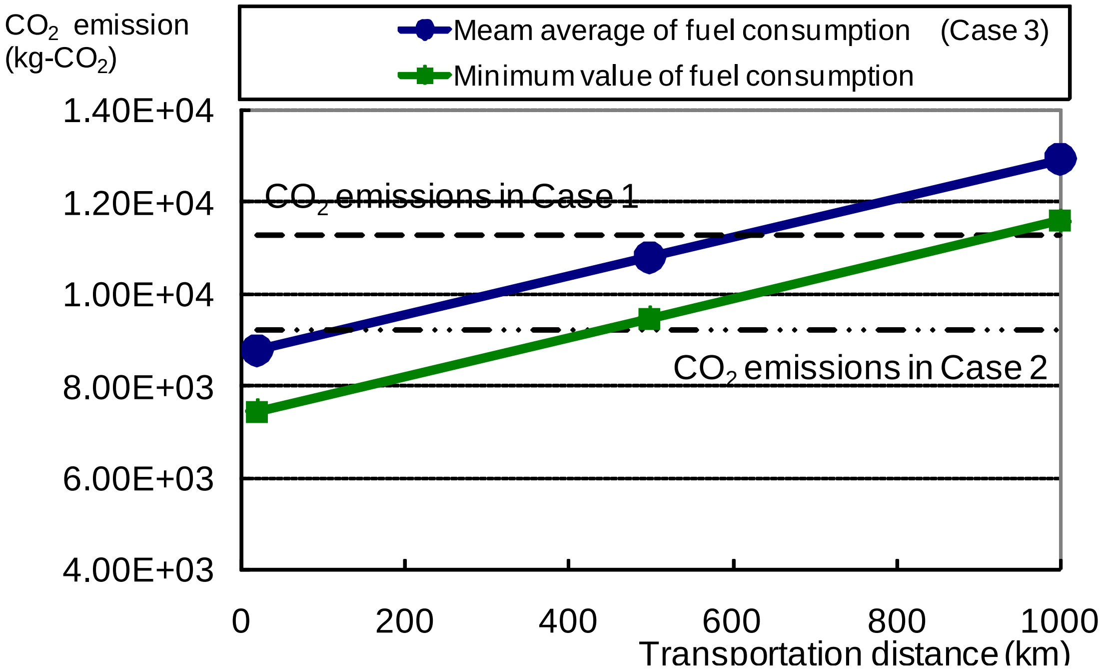


Figure 6. Comparison of in-place surface course recycling equipment by transportation distance

4. Conclusions

The results of this study are summarized below.

1) Concerning the CO_2 emissions in the respective emission stages from material production to waste disposal for the cut-and-overlay and in-place surface course recycling methods, the material production stage accounted for a high proportion of the emissions. With the cut-and-overlay in particular, the CO_2 emissions in this stage accounted for approximately 70% of the total. Concerning the material production stage, CO_2 emissions due to the production of asphalt mixture and asphalt were particularly great.
2) A comparison of CO_2 emissions between virgin aggregates and recycled aggregates with cut-and-overlay showed that total CO_2 emissions were less when recycled aggregates were used because the quantity of asphalt used and the quantity of aggregates transported were reduced, although the CO_2 emissions during the production of aggregates and asphalt mixture were greater than when virgin aggregates were used.
3) When the stages of asphalt mixture production and paving works were included, the CO_2 emissions with in-place surface course recycling were greater than with cut-and-overlay, for a recycled aggregates mix ratio of 60%. Nevertheless, the total amount of CO_2 emissions with in-place surface course recycling was small, because the CO_2 emissions during material transportation were small and because no waste material transportation was required.
4) Even with in-place surface course recycling which generates less CO_2 emissions, CO_2 emissions may increase depending on the distance that in-place surface course recycling equipment must be transported.

Future problems to be studied include the following:

1) The environmental loads generated by the machines used are greatly affected by those generated during the production of road cutters and in-place surface course recycling equipment. This was not considered in the present study and so should be considered in future studies.
2) The service life of pavement may vary depending on the use of either virgin or recycled materials, the use of either plant recycling or in-place recycling, and the use of various other paving technologies to supplement the pavement. Thus, CO_2 emissions should be estimated for the long term including the service life of pavement.
3) Changes of CO_2 emissions due to the combined use of energy-saving technologies during material production must be estimated. One such technology is the warm-mix technology, which is known to reduce CO_2 emissions by lowering the heating temperature when producing asphalt mixture to reduce the fuel consumed for heating. Accordingly, the increase in CO_2 emissions for producing the warm-mix additives themselves must be examined.

References

1) Ministry of Land, Infrastructure, Transport and Tourism of Japan (MLIT). *Report on the Results of Investigating the State of Construction Byproducts for Fiscal 2005*, December 2006. (in Japanese)
2) Masaru TERADA, Hiroyuki SAKAMOTO and Kiyoshi KATAWAKI. Resource-saving and Energy-saving Pavement Estimated Based on Energy Consumption and CO_2 Emissions, *Pavement*, 30-2, February 1995. (in Japanese)
3) Ministry of Land, Infrastructure, Transport and Tourism of Japan (MLIT). *Manual of Standard Quantity Surveying for Civil Engineering Works for Fiscal 2007 (River and Road Edition).* (in Japanese)
4) Hiroyuki NITTA and Itaru NISHIZAKI. LCA Evaluation of Recycle Pavement Using Scrap Tire and Waste Plastic, *Journal of Pavement Engineering*, Japan Society of Civil Engineers, pp.79-86, December 2008.(in Japanese)
5) Japan Soap and Detergent Association (JSDA). *Outline of the LCI Data of Coconut Oil Fatty Acid*, January 2003. (in Japanese)